Quarterly Technical Summary

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INTRODUCTION

This report summarizes the progress on Air Force funded tasks within the Division between 1 November 1971 and 31 January 1972. At the present time, these activities are limited in scope and involve the efforts of only six staff. These activities, however, effectively complement other on-going activities within the Laboratory for the FAA. The four areas under investigation are: radar MTI technology, airborne graphical displays, the influence of propagation effects on CNI system performance and the analysis of various microwave landing guidance systems.

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CONTENTS

AIR TRAFFIC CONTROL

I. SUMMARY

The Air Traffic Control (ATC) program at Lincoln Laboratory is primarily funded by the Federal Aviation Administration (FAA) and is directed toward the development and exploitation of techniques and instrumentation for meeting future ATC data acquisition requirements. The Air Force ATC program at the Laboratory was initiated in fiscal year 1971 and has continued to explore areas of particular interest to the military.

For many years, development work on ATC within the Air Force has not received high priority; however, with the recent immergence of a more vigorous FAA program there have been signs of increasing military interest. The importance of this program to the Air Force should be evident, because the Air Force is the largest "fleet" operator and any changes in the communications on other airborne electronic equipment will have a high economic impact on the Air Force.

One goal of the Lincoln Laboratory ATC program is to apply technology developments undertaken for the military to the civilian ATC environment. Another goal is to understand the impact of civil ATC developments upon military operations. A third goal is to understand the unique military ATC problems.

This report summarizes progress on the relatively small military funded program, which involves work in four areas:

(a) Surveillance technology — moving target indication (MTI) studies
(b) Airborne traffic situation display (ATSD)
(c) Communications, navigation and identification (CNI) system
(d) Microwave landing guidance systems (MLGS)

II. SURVEILLANCE TECHNOLOGY

Studies of optimum MTI processing systems were continued and the sliding weighted discrete Fourier transform (DFT) MTI processor was simulated on the IBM 360 computer. It was found that this class of processor could achieve essentially optimum performance against receiver noise, but that the frequency side lobes introduced by the time-truncation of the incoming data interacted with the low frequency clutter to degrade the sub-clutter visibility. This problem was resolved by filtering the sampled data with a pulse canceler before taking the DFT. The signal-to-interference ratio (SIR) was used to compare the performance of the resulting processor. This is shown in Fig. 1 for the airport surveillance radar (ASR) parameters. The processor assumes that the radar in-phase and quadrature video signals are sampled at a 1-Mc rate. State-of-the-art A/D converters can do this only with a 10-bit word length. This corresponds to a clutter-to-noise ratio of 48 dB, the value used to plot the curve in Fig. 1. When the corresponding signal-to-noise (SNR) ratio is 4.25 dB, the DFT processor results in an output SNR of 13 dB. Since this represents the minimum value needed for good detection performance, the sub-clutter visibility (SCV) is 44 dB. The valleys in the DFT curve show the
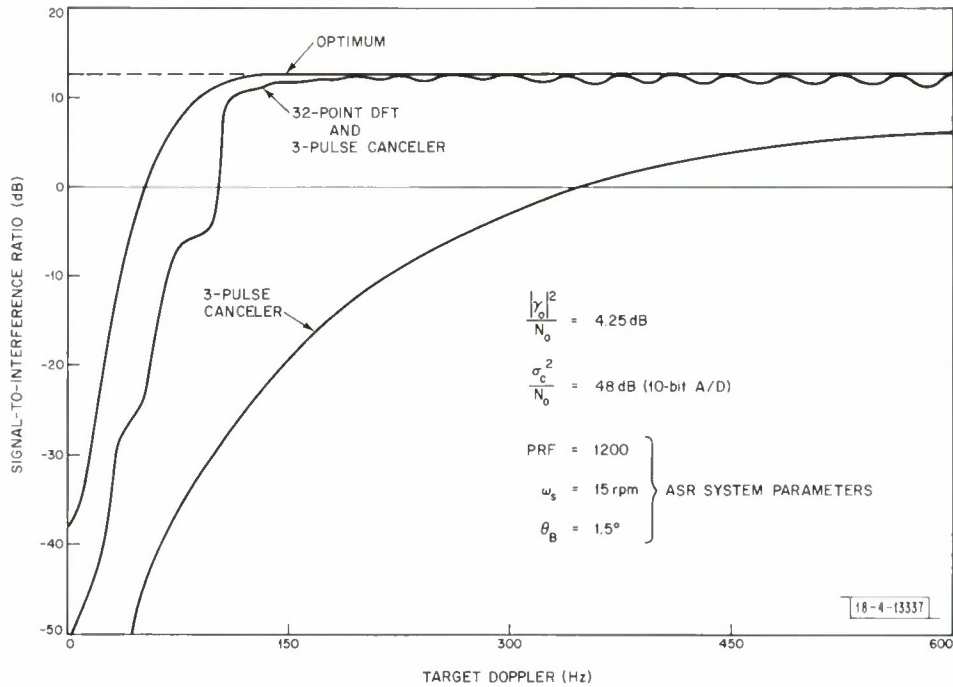
Fig. 1. ASR performance curve.

degradation in the SIR that occurs when the true target Doppler is located halfway between DFT coefficients.

In the next quarter, the simulation will be expanded to include the effects of pulse stagger-ing, and a technical note documenting the MTI signal design problem will be completed.

III. AIRBORNE TRAFFIC SITUATION DISPLAYS

Final checkout of the hardware for a demonstration ATSD is under way and is scheduled for completion in late February. This equipment is suitable for: (a) installation in a simulator; (b) a stand-alone demonstrator; and with some repackaging, (c) a military or civilian aircraft. The display equipment is interfaced to a small digital computer and the development of software for the combined unit is under way.

Study efforts are under way on a low-cost version of the airborne elements of an ATSD. The objective is to reduce the parts cost below $1000, while still retaining traffic, map and weather display capability.

In parallel with the hardware development effort discussed, a study of the utility of the ATSD in the ATC system of the 1980s is being conducted for the Aviation Advisory Commission. A preliminary draft of the conclusions from this study has been completed. The main conclusion is that the ATSD will bring into the cockpit information of value to the pilot in a format common to that used by the controller, and will thereby increase controller-pilot coupling. This in turn will help produce an environment in which ATC system improvements, such as higher levels of automation and reduced spacings, become more readily acceptable. The ATSD capability ap-pears to effectively complement and is compatible with the upgraded third generation ATC system.

2

IV. COMMUNICATIONS, NAVIGATION AND IDENTIFICATION SYSTEM

Under the sponsorship of the Air Force Electronic Systems Division, a study is under way to understand the impact of propagation phenomena on the choice of a modulation scheme for use in CNI systems. A variety of links, including air-to-air and air-to-ground, are being investigated along with the combination of operating modes and propagation effects.

The basic propagation phenomena can be conveniently catalogued in three broad classes. These are: (a) surface-reflected multipath; (b) atmospherically caused effects; and (c) aircraft-produced effects (e.g., multipath encountered with large airframes can have differential delay times on the order of 10 to 250 nsec.)

To identify critical but not sufficiently well understood aspects of the channel, we have evolved a propagation model to account for ground reflection multipath based in part on theoretical analysis and in part on previously obtained experimental results. Certain aspects of the model are described in Section IV-A. The results of an analysis of the performance degradation on spread spectrum signaling schemes due to ground reflection multipath are described in Section IV-B.

A. Propagation Model

A first-order propagation model has been developed to provide engineering estimates of the power reflected from non-smooth terrain. Exact theoretical results are not available for the general case. Approximate expressions have been examined. Those chosen were selected because: (1) they fit much of the available data reasonably well; and (2) their analytic simplicity is in keeping with their inherently approximate nature. It has been observed in past surveys of the relevant literature that much of the experimental data available or their interpretation is controversial. However, there are sufficient acceptable data to estimate certain important effects.

It is convenient to model the field scattered by a rough surface as the sum of a specular and a diffuse component. The amplitude and phase of the specular component are assumed to be deterministic.* The specular field is assumed to obey Snell's Law. The ratio of power in the specular component to the incident field is defined to be the specular reflection coefficient, $|R_s^{\pm}|^2$, where the superscripts + and − are used to indicate vertical and horizontal polarization components respectively. It is convenient to define $|R_s^{\pm}|^2$ as

$$|R_s^{\pm}|^2 = |R_o^{\pm}|^2 \, D^2 \, |\rho_s|^2$$

where $R_o^{\pm}$ is the classical Fresnel reflection coefficient for a smooth surface, D is the divergence factor which accounts for the effect of the curvature of the earth and ρ_s is the specular scattering coefficient, which accounts for attenuation in the specular power due to surface roughness.

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* The definitions of specular and diffuse reflection components vary slightly with some authors. The nomenclature coherent and incoherent is often used for specular and diffuse, respectively.
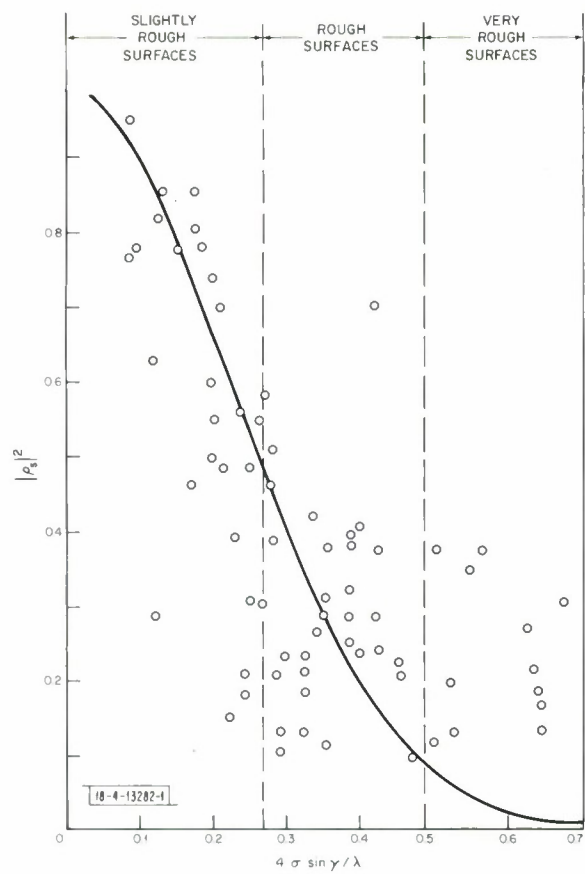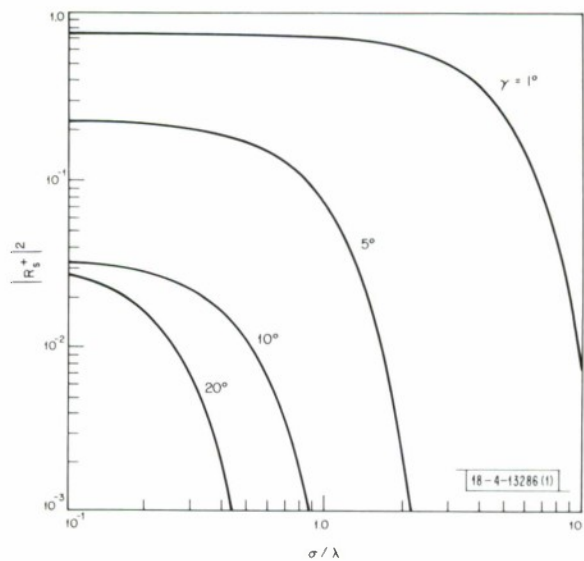
Fig. 2. Scattering coefficient for specularly reflected power vs apparent surface roughness (from data in Ref. 1).

Fig. 3. Specular reflection coefficient vs roughness for "standard earth" and vertical polarization.

4

The parameter $|\rho_s|^2$ has been calculated[1] assuming a Gaussian distribution of surface height with variance σ^2 and a perfectly conducting surface to be

$$|\rho_s|^2 = \exp\left[-\left(\frac{4\pi\sigma\,\sin\gamma}{\lambda}\right)^2\right]$$

where γ is the surface grazing angle for specular reflection and λ is the wavelength. This result is plotted in Fig. 2. As indicated by the variety of experimental data points plotted in Fig. 2, there is reasonable agreement with the model especially for slightly rough surfaces.

We plot, as an example, the specular reflection coefficient for "standard earth" and vertical polarization in Fig. 3. It is seen that for grazing angles of a few degrees or less, almost all of the incident power is specularly reflected.

The diffuse component of the field is conveniently modeled as a random vector both in amplitude and phase. If $R_d^{\pm}$ is the diffuse reflection coefficient, then the average fraction of incident power in the diffuse component can be expressed as

$$\overline{|R_d^{\pm}|^2} = \overline{|\rho_d|^2}\,|R_o^{\pm}|^2$$

where ρ_d is the diffuse scattering coefficient. Analytic estimates of $\overline{|\rho_d|^2}$ have proved difficult; however, available experimental data[2] provide a guide to first order estimates of the
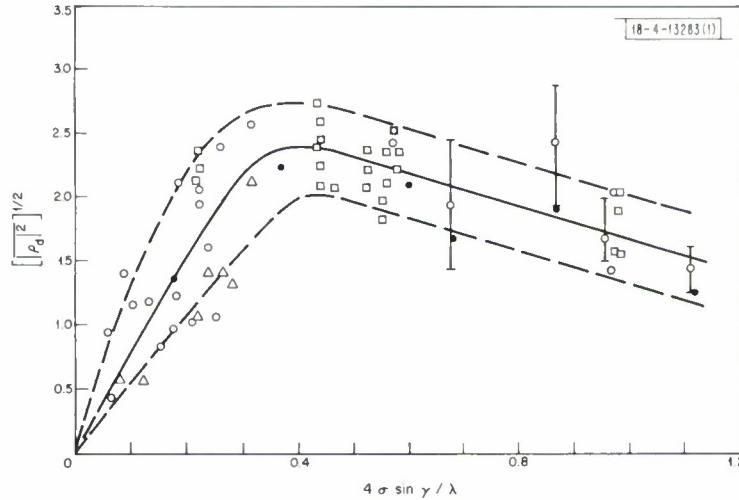

Fig. 4. Relative incoherent field strength vs apparent ocean roughness (from data in Ref. 2).

level. These are summarized in Fig. 4. These data were taken over water under varying sea-state conditions and at various frequencies. The solid curve represents a good estimate for a first order model.

B. Performance Degradation

Using the power estimates of the previous section we have calculated the performance degradation on certain spread spectrum signaling schemes due to reflection multipath. We have considered two categories of spread spectrum signals, i.e., coded frequency hopping-frequency

shift keying (FH/FSK) and pseudo-noise phase shift keying (PN/PSK). We have assumed a chan-
nel model in which the received waveform is a sum of four components: a direct (path) signal,
a specularly reflected signal, a diffusely reflected signal and an additive white Gaussian noise.
The specular component is assumed to be deterministic and coherent in nature and the diffuse
component is assumed to be a random process. Results have been obtained for the case in which
the differential time delay, τ, between direct and reflected paths is larger than the reciprocal
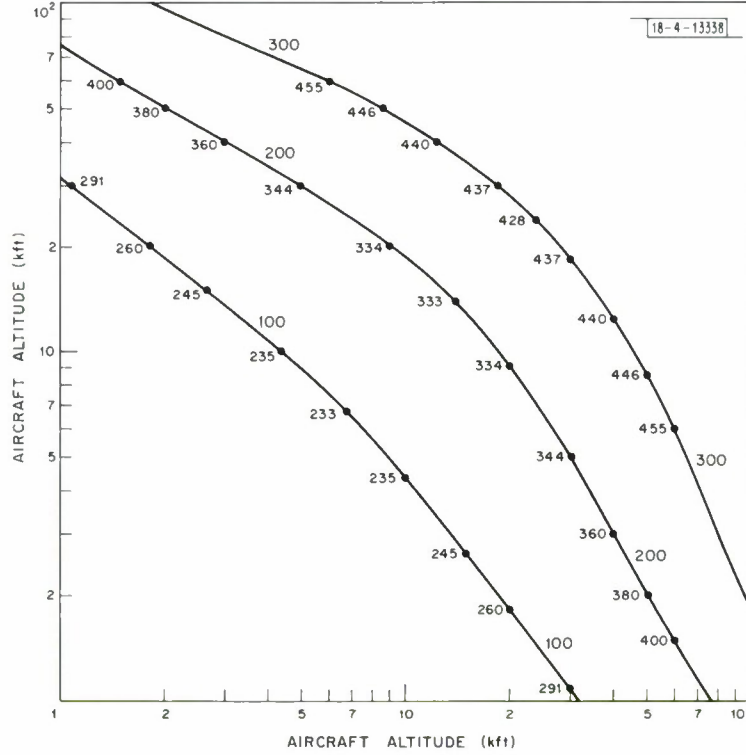

Fig. 5. Locus of aircraft altitudes corresponding to 100-nsec delay between direct and surface
reflected signal for aircraft separation of 100, 200 and 300 miles.

of the spread spectrum bandwidth, W. The restriction $\tau W > 1$ for a 10-MHz bandwidth is in-
terpreted for an air-to-air link in Fig. 5. Here we have the range of altitudes for two aircraft
corresponding to a differential time delay of 100 nsec (i.e., 10-MHz bandwidth) for an aircraft
separation of 100, 200 and 300 miles. For convenience, distance to the radio horizon is also
shown on each curve.

We have chosen as a measure of performance the efficiency factor

$$\eta = \frac{E_c/N_o}{R_o(E_c/N_o)}$$

where E_c is received energy per chip* over the direct path, N_o is the (single sided) background
noise power density and $R_o(\cdot)$ is the computational cut-off rate.[3] The efficiency η is often used

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* For the assumed digital modulation, the modulator is conveniently envisioned as a device which accepts digital inputs and pro-
duces an analog signal. If the basic modulator digital input is a digit to the base m, a chip is one of the m analog output signals
produced by the modulator.

to assess performance of modulation-demodulation systems and channels.[4] The interpretation of η depends on the precise application of the signals. For example, if the outputs were to be sequentially decoded, η would represent the minimum required energy/bit/noise power density. In systems employing other practical techniques for achieving reliability through redundancy, such as maximum likelihood convolutional decoding, performance as measured by bit error probability increases exponentially with η.

In Fig. 6 we present for illustrative purposes the results of one of these calculations; in particular, we plot η for coded 8-ary FH/FSK; i.e., information is coded and then transmitted by selecting one of 8 frequencies for various levels of specularly reflected power and no power in the diffuse path. We have neglected losses due to receiver quantization which in practice result in small additional losses. More significantly, the loss due to ground reflection multipath should change very little with and without quantization for well designed quantizers.[5] From Fig. 6 it is clear that at low values of chip signal-to-noise ratio (E_c/N_O), specular reflection improves system performance. In this case, the potential degradation resulting from destructive interference between the direct and specular paths is outweighed by the improved SNR under constructive interference conditions. At high values of E_c/N_O, the reverse condition is true. The degradation in η is at most 2 dB. However, with proper selection of the design point, e.g., E_c/N_O of 5 dB, the degradation can be kept even smaller. The addition of a diffuse return at the levels indicated in Sec. IV-A has an even smaller effect on the efficiency.

We have also analyzed PN/PSK signaling schemes and have demonstrated that for most cases of practical interest they suffer little due to reflection multipath. For example, we have shown that to communicate with binary uncoded PN/PSK at a 10^{-3} error probability requires less than 2 dB more signal power under severe multipath conditions (as estimated by the above model) than in the absence of multipath for data rates not in excess of 10 percent of the spread spectrum bandwidth. Coded PN/PSK systems tend to have performance superior to uncoded PN/PSK systems.

Fig. 6. Efficiency for 8-ary FH/FSK with the ratio of specular energy to direct energy (E_s/E_c) equal to 0.0, 0.3, 0.6 and 1.0.

V. MICROWAVE LANDING GUIDANCE SYSTEM

Study is continuing on microwave landing guidance systems (MLGS) with emphasis on defining critical technical issues. During the past quarter we have prepared a preliminary
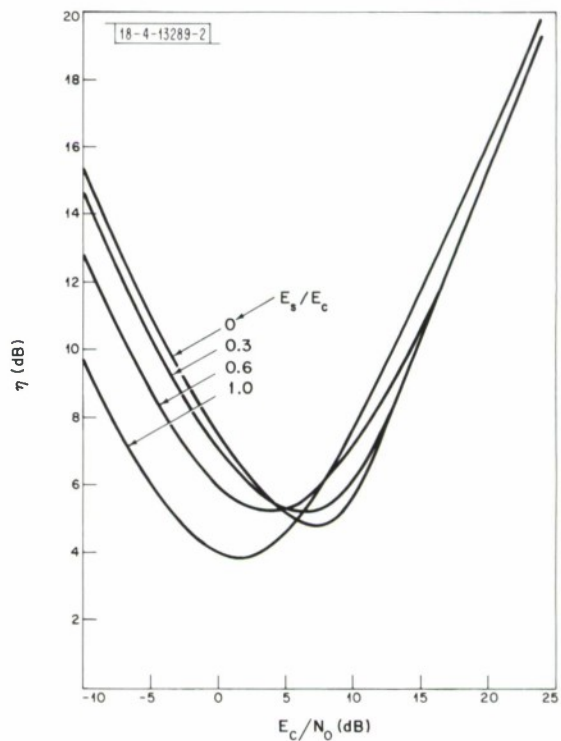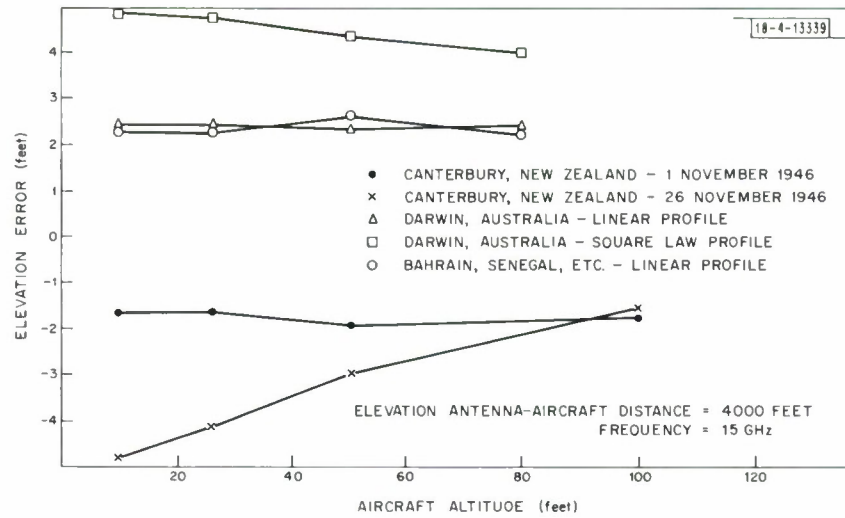
Fig. 7.   Elevation errors due to refraction for selected profiles.
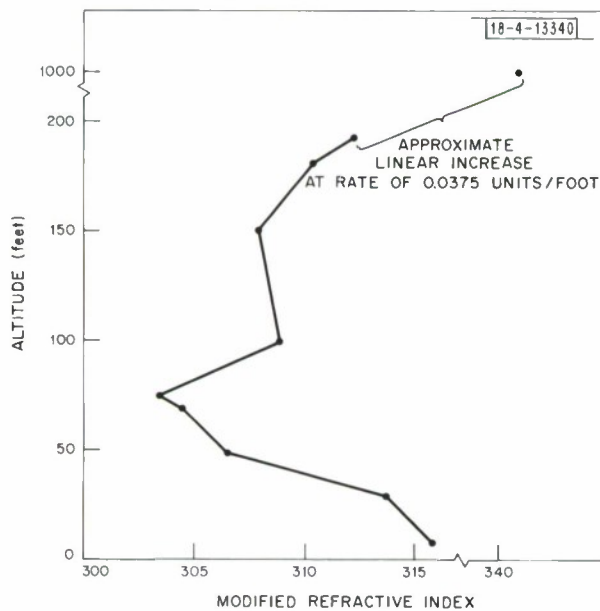

Fig. 8.   Modified refractive index profile measured 8 km inland at Canterbury, New Zealand, on 1 November 1946 from 1046 to 1118.

estimate of some of the critical propagation effects described in the last Quarterly Technical Summary.[6] These indicate that:

    (a) Atmospheric refraction effects can result in elevation errors several times larger than that permissible for a Category II landing facility.

    (b) Multipath reflection from buildings, hills or other aircraft can be received at the aircraft at a power level within 0.5 dB of the direct path signal.

    (c) Multipath reflection from the ground can result in elevation errors an order of magnitude larger than that permissible for a Category III landing facility.

A. Refraction Effects

The most severe refraction effects (i.e., bending of the landing system beam) should occur on the elevation (i.e., guide slope) signal, inasmuch as the vertical variation of refractive index is generally very much greater than the horizontal variation for the ray paths of interest.

Previous work[7] in predicting the magnitude of these effects for a MLGS focused on the elevation 1 datum, which provides guidance at angles above 1°, and concluded that the bending effects should be negligible for glide slopes above 1° to 2°. A similar conclusion follows from recent work[8] on satellite communication systems.

However, a key element of the proposed MLGS is the elevation 2 datum, which is to provide guidance for flareout down to touchdown. The proposed siting plan configuration for the elevation 2 datum indicates (see page A-7 of Ref. 9) that vertical guidance is required at elevation angles down to 0.057°. At such angles, significant errors due to refraction have been observed in satellite communications.[8]

ln Fig. 7 we show the elevation error due to refractive bending that would be encountered by the proposed MLGS at various aircraft altitudes for an elevation 2 antenna-aircraft distance of 4000 feet. These errors were computed by tracing ray paths, given profiles of refractive index vs height. The Canterbury, New Zealand data* represent closely-spaced measurements at various heights obtained from tethered balloons.[10] The other curves were obtained by assuming various profiles (either linear or square law) given only the net refractive index change over a layer.[11]

The bending errors shown in Fig. 7 are considerably larger than the 0.7-foot vertical bias errors desired for the MLGS.[9] Thus, it appears that refractive effects could have an important influence on design and performance of a MLGS.

The available refractive indexes are generally taken with radiosondes that make measurements at ground and every 1000 feet altitude. Such measurements cast little light on the variations over 0 to 200 feet, as is obvious from the Canterbury project data.[10] For example, in Fig. 8 we show the profile used in developing the bending errors shown in Fig. 7, together with the 1000-foot reading at the same time period.

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* The Canterbury data were obtained 8 km inland from the east coast of New Zealand. The marked change in refractive index was caused by warm dry air from the west moving out over a cold ocean, thus producing marked vertical gradients in temperature and humidity.

Refractive data, obtained using microwave refractometers on flights into clouds, indicate that quite pronounced refractive index changes can occur on entering and within the cloud. Thus, it may be possible that pronounced changes could also occur when fog banks lie above the ground.

A more complete investigation of errors resulting from refractive bending will require either detailed refractive index profiles from 10 to 300 feet altitude and/or direct measurement of beam bending. To our knowledge, there are no currently available data of the type described above. Experimentally measuring the humidity profile in the presence of clouds and/or fog is quite difficult, and it may be better to consider direct measurement of beam bending in appropriate locations. Such a direct measurement could also take into account any horizontal inhomogeneity that may exist. The results of such data are essential for assessing compensation techniques for a MLGS.

B. Multipath Interference

Multipath interference due to reflections from hangars, other aircraft, the ground, etc., have long been recognized as a serious problem with the current Instrument Landing System (ILS) which operates at frequencies of approximately 110 MHz (for the localizer) and 330 MHz (for the glide slope). In view of the multipath difficulties encountered with the ILS, it would appear that detailed consideration of multipath effects on MLGS performance is necessary before alternative signal format concepts, frequency of operation and antenna characteristics can be adequately addressed. In this section, we outline some general considerations involved in such a study of multipath effects and indicate the magnitude of effects that could arise in some common situations.

Past experience with early versions of a MLGS indicates that it is generally less susceptible to multipath as a consequence of:

(1) The narrow beamwidths used.

(2) The fact that ground reflection is not used to generate the vertical elevation signal.

(3) The shorter wavelength, which means that the reflection from many moderately rough surfaces is diffuse rather than specular.

(4) The shorter period of time for the aircraft to move through a cycle of net phase shift between the direct signal and the net reflected signal.

However, there are a number of aspects of multipath analysis that are significantly different for the MLGS, such that extrapolation from ILS experience (such as proposed in Ref. 12) can be misleading. These new aspects include:

(1) The fact that many cases of reflection that previously could be considered as a far-field (i.e., Fraunhofer field) problem are now in the near field (i.e., Fresnel field), as a consequence of the 50-fold decrease in wavelength (the far field is generally taken to be distances $\geqslant D^2/\lambda$, where D is the largest reflecting object dimension). The amplitude of the multipath will generally be much larger in the Fresnel region (see the result below for an aircraft near the end of a runway).

10

(2) For specular reflectors such as flat plates (e.g., hangar walls, tail fins, etc.) and cylinders (e.g., fuselages), the specular component of the far-field reflection is proportional to $1/\lambda^2$ and $1/\lambda$, respectively. Thus, such reflectors may be more significant at microwave frequencies than at the ILS frequencies.

(3) The rapid variation in multipath characteristics as a function of transmitter-scatterer-receiver orientation means that adequately characterizing the multipath environment by experimental measurements may require significantly more care, as well as a careful prior investigation into the critical aspects of the temporal multipath structure insofar as MLGS performance is concerned.

To illustrate some of the points made above, we consider a few multipath situations that could arise in a typical airport environment. The first case, illustrated in Fig. 9, involves a
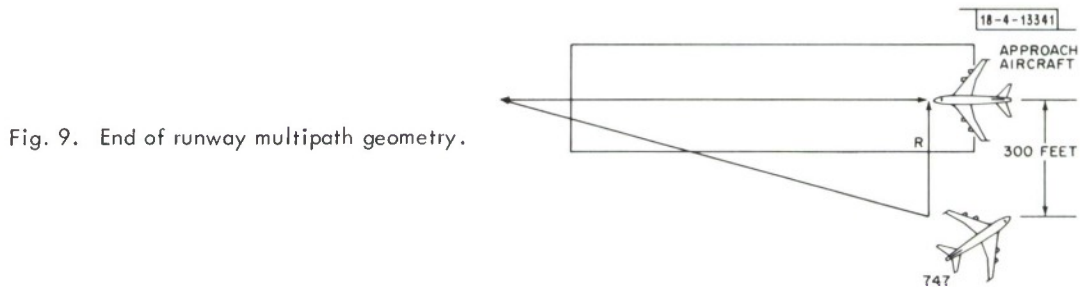

Fig. 9. End of runway multipath geometry.

747 jet parked 300 feet from the end of the 12,000-foot runway at which another plane is landing. We assume the 747 is located so that the specular reflection from the tail will be in the path of the landing plane and that the tail can be modeled by a flat plate. With these assumptions and the tail plane dimensions from Ref. 13 we find that

(1) At C band, the landing aircraft is in the Fresnel region of the tail plane. Straightforward calculation (see page 70 of Ref. 14) shows that the multipath reflection over a runway distance of approximately 45 feet (= horizontal width of tail plane × sin 45°) has a magnitude of approximately ±0.5 dB with respect to the direct component.

(2) At the ILS localizer frequency, the landing plane is in the far-field region of the tail plane. Since the tail plane dimensions are several times the wavelength, we use the scattering cross-section formula for a plate and find that the multipath reflection is approximately 19 dB below the direct component.

In Fig. 10 we show a case where there is specular return off a hill or a building that is well removed from the landing path. Proceeding as above, we find that

(1) At C band, the aircraft is in the Fresnel region and will encounter multipath of approximately ±0.5 dB with respect to the direct component over a distance of 267 feet (= 500 feet × sin 58°).

11

(2) At the ILS localizer, the aircraft is on the far field and will encounter a peak multipath level that is approximately 36 dB below the direct component.

The above calculations indicate that significant multipath can be encountered at plausible geometries. Future analysis should assess the magnitude of the effects of reflection multipath on one plane following another down a glide slope.
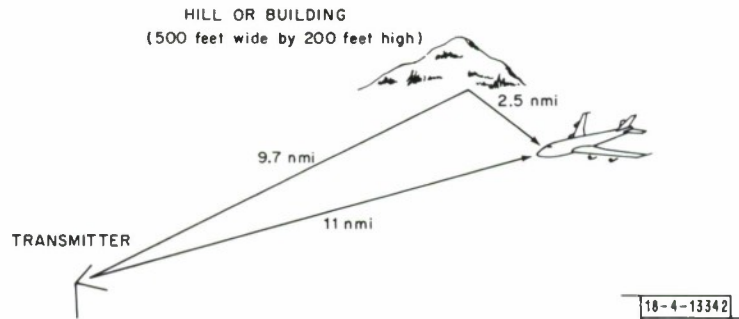

Fig. 10. Geometry for multipath off a hill.

C. Multipath Induced Beam Bending

At low elevation angles, ground reflections can distort the flareout-to-touchdown elevation signal. The resulting distortion in beam pattern and the resulting error in elevation have been calculated assuming a 0.5°-beamwidth antenna, a reflection coefficient corresponding to very wet soil and an aircraft 3000 feet from the elevation 2 datum. The results indicate that for an aircraft at 50 feet altitude the indicated elevation can be as large as 1.8 feet above the true elevation, while for an aircraft at 15 feet altitude the indicated elevation can be as large as 14.1 feet above the true elevation. The errors should be contrasted with the 1.4-foot two sigma bias specified by RTCA.[9]

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13. ABSTRACT

This report summarizes the progress on Air Force funded tasks within the Division between 1 November 1971 and 31 January 1972. At the present time, these activities are limited in scope and involve the efforts of only six staff. These activities, however, effectively complement other on-going activities within the Laboratory for the FAA. The four areas under investigation are: radar MTI technology, airborne graphical displays, the influence of propagation effects on CNI system performance and the analysis of various microwave landing guidance systems.

14. KEY WORDS

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